Some Geologic Features of the Pima Mining District Pima County, Arizona

GEOLOGICAL SURVEY BULLETIN 1112-C

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By JOHN R. COOPER

CONTRIBUTIONS TO ECONOMIC GEOLOGY

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A preliminary report including a discussion of the Helmet fanglomerate and its structural implications

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SOME GEOLOGIC FEATURES OF THE PIMA MINING DISTRICT, PIMA COUNTY, ARIZONA

By John R. Cooper

ABSTRACT

Rocks ranging in age from Precambrian to Recent crop out in the Pima district. Granite, which locally contains many large inclusions of schist and hornfels, is believed to be Precambrian, as it appears to be overlain unconformably by the Bolsa quartzite of Middle Cambrian age. Probably all the Paleozoic formations of the region are represented, but only the Bolsa quartzite, at the base of the Paleozoic section, has been differentiated on the geologic map. Overlying the Paleozoic rocks is a complex of sedimentary and volcanic rocks assigned to the Cretaceous(?). Sedimentary units include conglomerate, arkose, graywacke, quartzite, shale, and a few thin beds of limestone. Volcanic units include andesitic and rhyolitic types. The stratigraphic sequence within the Cretaceous(?) complex is not known. Preliminary subdivisions based on lithology are shown on the map.

Diorite, andesite, granodiorite, and quartz monzonite porphyry postdate the Cretaceous(?) complex and are assigned to the Late Cretaceous or early Tertiary. These rocks, with the possible exception of some of the diorite and andesite, were intruded after a major orogeny that affected the Cretaceous(?) complex. They are all mineralized locally. The quartz monzonite porphyry, which is probably the youngest of these rocks, is associated in space with several large copper deposits, suggesting that porphyry and ore are related genetically.

In one part of the district, folded and faulted Cretaceous(?) rocks are unconformably overlain by a welded rhyolitic tuff. It is not clear whether the tuff is older or younger than the ore.

A deformed postmineralization formation, here named the Helmet fanglomerate, overlies the ryholitic tuff unconformably. The fanglomerate consists predominantly of coarse, ill-sorted and ill-bedded conglomerate characterized by angular pebbles, cobbles, and boulders in an abundant silty matrix. Intercalated are lava flows of porphyritic andesite, scarce thin beds of rhyolitic tuff and tuffaceous sediments, and lentils and tongues of monolithologic breccia which appear to have been emplaced as landslides. Several stratigraphic units are indicated by variations in color, composition of fragments, sedimentation features, and presence or absence of tuffaceous material. The formation is probably at least 10,000 feet thick. It is believed to be made up of alluvial-fan deposits derived from the west, southwest, or northwest. No fossils have been found, but tentative correlations suggest that the fanglomerate may be of early Miocene age.

Andesite dikes cut the Helmet fanglomerate; and Quaternary alluvial deposits cover much of the central and eastern part of the area described.

The structural relations of the Helmet fanglomerate indicate two orogenies that postdate the Cretaceous(?) rocks. The earlier, pregranodiorite and premineralization, resulted in complex fold and fault structural features that trend

northwest. The later, post-mineralization and post-Helmet, resulted in a large thrust fault and steep tilting to the southeast.

Rotational effects of the post-Helmet orogeny must be removed to restore the structure at the time of mineralization.

The San Xavier thrust fault beneath the northeastern part of the district cuts the Helmet fanglomerate and is therefore a postmineralization thrust. Small faults in boulders of the fanglomerate in the thrust plate suggest that the plate moved north-northwest. Similarities in the geology of the plate and of the autochthonous block to the south suggest that the plate moved about 6½ miles north-northwest.

INTRODUCTION

The Helmet fanglomerate in the Pima mining district is a deformed postmineralization formation of Tertiary age. Where the fanglomerate is present, it forms a thick blanket over the potentially ore-bearing rocks. It also provides a basis for distinguishing late Tertiary from older structural features. The purpose of this report is to describe the fanglomerate and discuss the postmineralization structure that can reasonably be inferred. Color terms used to describe the rocks are those of the "Rock-Color Chart" of the National Research Council (1948). The roundness of sedimentary particles and their size (Wentworth scale) are described in terms adopted by the American Geological Institute (1958).

The Pima mining district is an old copper, lead, zinc, and precious-metal district in Pima County, Ariz., 15 to 30 miles by road south-southwest of Tucson (fig. 15). The district promises to become one of the major sources of copper in the United States as a result of the recent discovery of several large deposits.

The principal new discoveries in the district have been made by four mining companies and include those at and near the Mineral Hill, Daisy, and Glance mines of the Banner Mining Co. (Bowman, 1955; Storms and Bowman, 1957; anonymous, 1958a and 1959b), the Pima open-pit mine of the Pima Mining Co. (Thurmond, Heinrichs, and Spaulding, 1954; Thurmond and Storms, 1958; Thurmond, Olk, and others, 1958), the Esperanza open-pit mine of the Duval Sulphur and Potash Co. (anonymous, 1957, 1958b, and 1959a), and the Mission deposit (once called the East Pima deposit) of the American Smelting and Refining Co. (anonymous, 1957, 1958b, and 1959c).

Some geologic information on the district is given in the reports just referred to and also in brief reports by Ransome (1922), Webber (1929), Wilson (1941, p. 36–37; 1950, p. 39–51), Cummings and Romslo (1950), Lacy (1959), MacKenzie (1959), Irvin (1959), Journeay (1959), Richard and Courtright (1959), and Schmitt and others (1959). Additional data are available at the University of Arizona

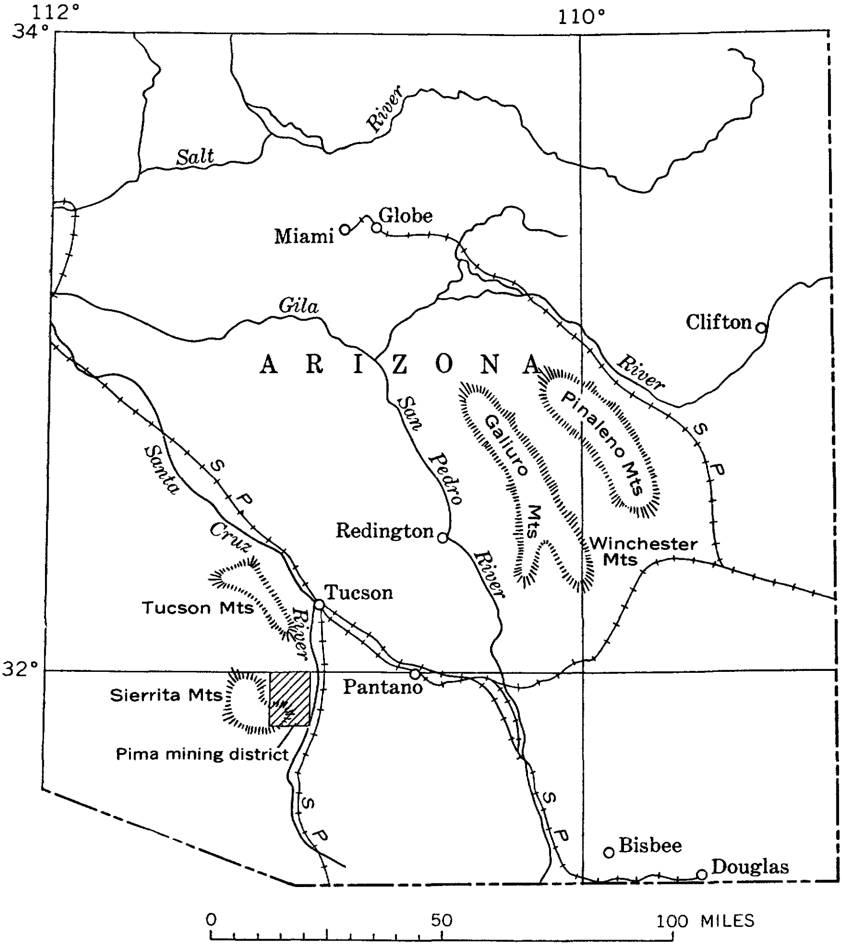

FIGURE 15. Index map of southeastern Arizona showing the location of the Pima mining district.

in eight unpublished theses by geology students[1] and in a Survey open-file report by Anderson and Kupfer (1945).

The present report is the first product of a geologic study of the district started in the fall of 1957 by the U.S. Geological Survey. J. H. Stewart and J. C. Wright assisted me for a month each at the start of the project, and A. R. Conroy assisted from October 1958 to June 1959.

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[1] The papers following are on file at the University of Arizona Library.

Gorden, E. R., 1922, The geology of the Twin Buttes mining district: Arizona Univ. M.S. thesis, 10 p., 3 illus.

Brown, R. L., 1926, Geology and ore deposits of the Twin Buttes district: Arizona Univ. M.S. thesis, 40 p., 12 pl., 15 fig. (Footnote continues on next page.)

Mining-company employees and others familiar with the Pima district have cooperated in many ways. Especial acknowledgment is due: Messrs. K. E. Richard, J. H. Courtright, and J. E. Kinnison, of the American Smelting and Refining Co.; Messrs. A. B. Bowman and F. D. MacKenzie, of the Banner Mining Co.; Messrs. G. E. Atwood, D. M. Klippinger, and W. J. Roper, of the Duval Sulphur and Potash Co.; Messrs. W. D. Nelson and G. W. Irvin, of the McFarland and Hullinger Co.; Messrs. E. D. Spaulding and J. A. Journeay, of the Pima Mining Co.; Mr. W. R. Jones of the U.S. Geological Survey; and Messrs. R. C. Cribbs, T. A. Dodge, E. D. Wilson, and H. A. Schmitt, of Tucson, Ariz.

PHYSIOGRAPHIC SETTING AND GENERAL GEOLOGIC FEATURES

The Pima district is on the northeast flank of the Sierrita Mountains in the Basin and Range physiographic province. The southwestern part of the district, which contains the Esperanza (Duval) mine, is in foothills that are continuous with the main part of the mountains. The rest of the district is beneath an extensive pediment. This pediment is not perfectly even but is trenched by shallow arroyos and surmounted by isolated hills, such as Mineral Hill, Helmet Peak, and Twin Buttes, which are conspicuous landmarks. Alluvium of Santa Cruz valley overlaps the eastern part of the pediment and is about 200 feet thick over the large Pima and Mission ore bodies.

The rocks exposed in the district include an upper Cretaceous or lower Tertiary granodiorite to the west and a complex of faulted and folded sedimentary and igneous rocks to the east and south (pl. 1). Ore mineralization followed intrusion of the granodiorite and of a quartz monzonite porphyry that is either a facies of the granodiorite or a genetically related intrusive rock. Important clues to the structural history are provided by the postmineralization Helmet fanglomerate, which has not been described heretofore. In this report the rocks of the district are grouped for convenience as (a) rocks older than the Helmet fanglomerate, (b) the Helmet fanglomerate, and (c) rocks younger than the Helmet fanglomerate.

Park, C. F., Jr., 1929, Geology of the San Xavier district: Arizona Univ. M.S. thesis, 30 p., 3 illus.

Eckel, E. B., 1930, Geology and ore deposits of the Mineral Hill area, Pima County, Arizona: Arizona Univ. M.S. thesis, 51 p.

Mayuga, M. N., 1942, The geology and ore deposits of the Helmet Peak area, Pima County, Arizona: Arizona Univ. Ph. D. thesis, 124 p.

Whitcomb, H. A., 1948, Geology of the Morgan mine area, Twin Buttes, Arizona: Arizona Univ. M.S. thesis, 82 p., 17 pl.

Houser, F. N., 1949, The geology of the Contention mine area, Twin Buttes, Arizona: Arizona Univ. M.S. thesis, 71 p., 18 pl.

Lutton, R. J., 1958, Some structural features of southern Arizona: Arizona Univ. M.S. thesis, 138, p., 46 pl.

ROCKS OLDER THAN THE HELMET FANGLOMERATE

PRECAMBRIAN GRANITE

Granitoid rocks of at least two ages crop out in the district; some are certainly Cretaceous or Tertiary, and others are probably Precambrian. This relation was suspected by Ransome (1922, p. 409–413) and is indicated on the Geologic Map of Arizona (Darton and others, 1924). Most later descriptions of the district state or imply that all the granitoid rocks are of Cretaceous or Tertiary age. I believe that Precambrian granite and Cretaceous or Tertiary granodiorite are present, though some modification of the preliminary map pattern (pl. 1) may be required after more work is done.

In a small hill 4½ miles southeast of the Pima mine, the lowermost Paleozoic formation, the Bolsa quartzite of middle Cambrian age, lies with gentle dip on granite. The quartzite has a basal conglomerate and truncates foliation in the granite. Though no fragments of granite were recognized in the basal conglomerate, the contact of the conglomerate and granite is almost certainly an unconformity.

The geologic relations, shown on plate 1 near Twin Buttes village and on the west side of Minēral Hill also suggest that the Bolsa quartzite was deposited on the granite and therefore that the granite is of Precambrian age. Wherever the granite was found in contact with post-Bolsa formations, the relation is due to faulting or is indeterminate because of poor exposures.

South of the latitude of Ruby Star Ranch, the Precambrian granite contains many large unmapped inclusions of schist and hornfels. A steep northwest-trending foliation is characteristic. What appears to be the least contaminated igneous rock has the mineral composition of granite or quartz monzonite. Its texture is uneven and variable and the rock is commonly a little coarser grained than the younger granodiorite. The principal field criterion used to distinguish the two rocks is the character of the biotite; the biotite in the older granite is in aggregates of tiny flakes, whereas the biotite in the younger granodiorite is in conspicuous books, which are commonly as high as they are wide. By using this criterion, the contact between granite and the small granodiorite body a mile northwest of Twin Buttes village can be defined within a foot. The contact between granite and the large granodiorite body west of Twin Buttes village is poorly exposed and is obscured by postgranodiorite alteration.

Most of the inclusions in the granite are fine-grained dark-gray schist and hornfels, presumed to be mafic metavolcanic rock derived from the Pinal schist of Precambrian age, which is nowhere exposed in the district. In the isolated hill 4½ miles southeast of the Pima mine, some of the included material is quartzite, also presumed to be from the Pinal. The inclusions are commonly cut by dikes and seams of granite, aplite, and pegmatite; and at a few places injection gneiss has been formed.

Granite containing many inclusions and resembling the rock near Twin Buttes crops out between Mineral Hill and the high hill just northwest of the San Xavier mine. West and southwest of this area the only inclusions found are in a wedge next to the granodiorite 3 miles west of Mineral Hill. Much of the intervening granite is medium to coarse grained and low in dark-mineral content. The grain size is not uniform, and large round grains and aggregates of quartz are characteristic. This facies of the granite is called the Sierrita granite by Lacy (1959, p. 186).

The typical Sierrita granite of Lacy contains masses of medium-grained rock with mineral composition and texture resembling some facies of the Cretaceous and Tertiary granodiorite. This rock is tentatively regarded as part of the Precambrian granite complex because it has a sharp contact with the granodiorite and appears to grade into the Sierrita granite. It is distinguishable from the adjacent marginal facies of the granodiorite by lack of hornblende and by smaller and less abundant books of biotite.

PALEOZOIC SEDIMENTARY ROCKS

Discontinuous masses of Paleozoic sedimentary rocks crop out within a few miles of Twin Buttes, and also in the Mineral Hill-Helmet Peak area. Most, if not all, of the Paleozoic formations of the region are represented; but the details of stratigraphy and structure are obscure because of complex faulting, widespread pyrometamorphism, and discontinuity of outcrop. The following formations have been recognized:

Pennsylvanian and Permian, Naco group:

- Concha limestone (Gilluly, Cooper, and Williams, 1954, p. 29–30)
- Scherrer formation (Gilluly, Cooper, and Williams, 1954, p. 27–29)
- Colina limestone (Gilluly, Cooper, and Williams, 1954, p. 23–25)
- Earp formation (Gilluly, Cooper, and Williams, 1954, p. 18–23)
- Horquilla limestone (Gilluly, Cooper, and Williams, 1954, p. 16–18)

Mississippian:

- Escabrosa limestone (Ransome, 1904, p. 42–44)

Devonian:

- Martin limestone (Ransome, 1904, p. 33–42)

Cambrian:

- Abrigo formation (Ransome, 1904, p. 30–33)
- Bolsa quartzite (Ransome, 1904, p. 28–30)

This list of formations is preliminary and may not be complete. Beds of shale, limestone, marl, and gypsum that crop out near the San Xavier mine and on Mineral Hill have been tentatively assigned to the Earp formation. On an isolated hill 1½ miles south-southeast of Twin Buttes village, a truncated anticline reveals beds with typical Earp lithology and fossils, flanked in part by dolomite beds that probably represent the base of the Colina limestone.

Detailed mapping of the Paleozoic formations will require a large-scale map and much more fieldwork than the Geological Survey has done to date. On the preliminary map (pl. 1) the Bolsa quartzite is shown separately in order to indicate some of the structural relations.

CRETACEOUS(?) SEDIMENTARY AND VOLCANIC ROCKS

A complex of sedimentary and volcanic rocks here considered to be of Cretaceous(?) age is exposed in the northeastern and southern parts of the Pima district. Sedimentary units include conglomerate, arkose, graywacke, quartzite, shale, and a few thin beds of limestone. Volcanic units include andesitic and rhyolitic types.

A lenticular limestone unit in arkose about half a mile south of Helmet Peak contains the remains of pelecypods, gastropods, and ostracodes. The gastropods and pelecypods found are indeterminable (J. B. Reeside, Jr., written communication, Apr. 25, 1958). Concerning the ostracodes, I. G. Sohn states (written communication, Sept. 23, 1958):

> . . . Very poorly preserved ostracodes of the fresh-water type common in Upper Jurassic through Recent sediments are present. Based on the ostracodes, the field designation of "Cretaceous" is neither confirmed nor denied. The ostracodes are definitely nonmarine. Gross morphology suggests the following nondiagnostic forms:
>
> *"Metacypris"* sp. or spp.—bisulcate type
> *Darwinula?* sp.

In the Tucson Mountains (fig. 15), 10 to 15 miles north of the Pima district, a limestone unit in the Amole arkose of Bryant and Kinnison has yielded well-preserved ostracodes of species that are very common in the nonmarine Jurassic and Lower Cretaceous rocks of the Rocky Mountain region but are unknown in Upper Cretaceous rocks (Bryant and Kinnison, 1954). The Amole arkose is lithologically similar to the arkose south of Helmet Peak; this similarity suggests that the latter is of Jurassic or Early Cretaceous age. The entire complex is herein referred to the Cretaceous(?).

The stratigraphy and the structure of the Cretaceous(?) complex are obscure. The lithologic subdivisions shown on the geologic map are generalized and subject to modification when more work is done.

Some small dikes are not shown, and some larger hypabyssal intrusive bodies may be included in the andesite and rhyolite units.

The basal unit of the complex may be exposed just south of Helmet Peak. The peak is underlain by the Concha, Scherrer, and Colina formations in an upright isoclinal anticline that plunges steeply south-southeast. Both limbs of the anticline are faulted and are bordered by Cretaceous(?) rocks. In small isolated outcrops less than half a mile southeast of the peak, a pebble and cobble conglomerate containing fragments of limestone is in apparent depositional contact on the Concha limestone on the projection of the fold. The conglomerate is unlike any known beds in the Paleozoic section and is interpreted as the basal unit of the Cretaceous(?) sequence.

According to this interpretation the basal conglomerate is confined to the narrow fault block that contains the anticline, and therefore is out of position with respect to the Cretaceous(?) rocks that border the fault block. The direction and the amount of displacement on the bounding faults are not known. Large displacement is suggested by discordances in bedding attitudes within the fault block from attitudes on the two sides. Therefore no reliable conclusions concerning the general sequence of Cretaceous(?) units can be drawn.

UPPER CRETACEOUS OR LOWER TERTIARY INTRUSIVE ROCKS

Diorite, andesite, granodiorite, and quartz monzonite porphyry cut previously deformed rocks of the Cretaceous(?) complex and older formations. These intrusive rocks are probably of Late Cretaceous or early Tertiary age and are mineralized locally.

DIORITE

Biotite diorite is found in the southern part of the map area, as dikes and plugs in the Cretaceous(?) complex and as a large irregular body almost surrounded by granodiorite (in part somewhat atypical). The diorite is probably older than the granodiorite and quartz monzonite porphyry, for it is cut by what appear to be dikes and apophyses of these rocks. Small granitoid inclusions in the diorite indicate that there is an older granitic rock in the vicinity.

Tentatively mapped as diorite is the biotite-quartz granulite of Anderson and Kupfer (1945, p. 5), which crops out immediately northeast of the Esperanza mine. This rock, which resembles the typical diorite in some outcrops, is schistose locally and is injected by granodiorite and aplite. More work is needed to establish its age and correlation.

The typical diorite is a fine-grained medium-gray rock in which plagioclase and biotite are distinguishable with a hand lens. Some of the biotite is concentrated in dark clots several millimeters in diameter.

Examination of thin sections reveals the diorite from the large diorite body has intergranular texture. Laths of plagioclase (calcic andesine) make up about 60 percent of the rock and have subparallel orientation. Biotite and actinolitic(?) hornblende, in nearly equal amounts, make up much of the rest and have random orientation. Potassium feldspar and quartz rim and embay the other minerals, and are largely or wholly of replacement origin. Accessory minerals include magnetite, sphene, apatite, and epidote. The dark clots, so characteristic in most hand specimens, consist of aggregates of biotite, hornblende, and commonly magnetite dust. The ferromagnesian minerals appear to be replacement products. They lack the preferred orientation of the plagioclase and are commonly intergrown with one another and at places have a poikiloblastic habit. Secondary magnetite dust, sphene, and epidote are found as inclusions in them. It is quite possible that the original ferromagnesian mineral was pyroxene or amphibole different from the one now present. The biotite, potassium feldspar, and quartz may have resulted from silica and potassium metasomatism related to the granodiorite or quartz monzonite porphyry intrusions.

ANDESITE

In the southern part of the map area, dark-gray fine-grained igneous rock, classified as andesite by geologists of the Duval Sulphur and Potash Co., forms dikes and pluglike masses in the Cretaceous(?) complex. Some of the richest ore in the Esperanza mine is in small much-altered bodies of this rock (Harrison Schmitt, 1958, oral communication). The andesite is probably older than the quartz monzonite porphyry, for the porphyry contains inclusions of andesite and what appears to be a dike of the porphyry was found in one of the pluglike bodies of andesite. No field evidence bearing on the age of the andesite with respect to the diorite or granodiorite has been found.

The andesite is divisible into two textural varieties. One variety is nearly equigranular and so fine grained that plagioclase is the only mineral distinguishable with a hand lens. The other variety contains conspicuous phenocrysts of hornblende, commonly oriented by flow. I have made no microscopic study of either variety as yet.

GRANODIORITE

Granodiorite forms a large intrusive body in the western part of the district and smaller bodies in the eastern part (pl. 1). About 1½ miles southwest of Twin Buttes village, the large body cuts faulted Paleozoic and Cretaceous(?) beds which strike northwest and dip steeply. Tongues of granodiorite were intruded along and across some of the faults; this crossing proves that granodiorite emplacement followed an orogeny of Late Cretaceous or early Tertiary age.

The unaltered granodiorite is generally light gray, which in places has a pinkish, yellowish, or brownish cast. Three textural varieties grade into one another and are not mapped separately: (a) granodiorite porphyry found in small bodies and as a local border phase of the larger bodies; (b) medium-grained equigranular granodiorite found in the medium-sized bodies and in a zone ½ to 2 miles wide along the east side of the large body; and (c) porphyritic granodiorite found in the large body west of the equigranular facies. The granodiorite porphyry is characterized by abundant medium-sized crystals in a fine-grained groundmass. The porphyritic granodiorite contains sparse phenocrysts of potassium feldspar as much as 2 inches long in a medium-grained equigranular groundmass.

Quartz, feldspar, and books of biotite are evident in hand specimens of all facies of the rock. With a hand lens it is commonly possible to distinguish gray twinned plagioclase from slightly pinkish gray untwinned potassium feldspar and to discern small brilliant honey-colored crystals of sphene. In the eastern equigranular facies of the large body, hornblende is also common. This facies of the rock is further distinguished in some outcrops by the presence of ellipsoidal mafic inclusions generally less than 1 foot long.

As seen in thin section, the equigranular granodiorite and the groundmass of the porphyritic granodiorite have a hypidiomorphic-granular texture. Anhedral potassium feldspar and quartz are interstitial to euhedral or subhedral crystals of plagioclase, biotite, and hornblende (if present). The interstitial material in the granodiorite porphyry, in the single thin section examined, is a very fine textured granophyric intergrowth of quartz and potassium feldspar. In other respects the texture is similar to that of the equigranular facies.

The plagioclase in all the facies has the average composition of oligoclase and is commonly zoned from An_{25-40} in the centers of the grains to An_{8-15} at the rims. The potassium feldspar is generally microcline, but some lacks visible quadrille twinning and may be orthoclase. Some grains are perthitic. The mineral proportions, summarized in table 1, indicate that most of the rock is biotite-oligoclase granodiorite. Some contains a high enough proportion of potassium feldspar to be classified as quartz monzonite (analysis 6 and possibly analysis 7, table 1).

The granodiorite, as mapped, includes dikes and a few nearly equidimensional bodies of aplite and pegmatite. The aplite and pegmatite are most abundant near granodiorite contacts, both in the granodiorite and in the wallrocks. Several miles west of Helmet Peak, astride the contact of the granodiorite and the granite, dikes a few feet wide and 100 to 1,500 feet long are locally abundant enough to constitute 5 to 10 percent of the total bedrock. The trend of most of these dikes ranges from N. 50° E. through east to S. 80° E. A few dikes trend

TABLE 1.—*Modal analyses of Upper Cretaceous or lower Tertiary granodiorite*

Mineral	Large body				Smaller bodies		
	Equigranular facies		Porphyritic facies		Equigranular facies		Porphyritic facies
	1	2	3	4	5	6	7
Plagioclase	48	47	43	45	50	42	39
Potassium feldspar and perthite	19	19	10	18	22	25	4.0
Quartz	24	23	37	32	23	28	12
Granophyric quartz and potassium feldspar	--------	--------	--------	--------	--------	--------	28
Biotite and chlorite	5.5	6.3	5.1	3.4	3.3	3.1	11
Hornblende	2.3	2.4	--------	--------	--------	--------	--------
Myrmekite	Tr.	Tr.	1.6	.6	.4	.3	--------
Opaque minerals	.6	.8	.5	.7	.8	1.0	--------
Sphene and leucoxene	.5	.4	.8	.3	.3	.1	.1
Apatite	.1	.3	.2	.1	.3	.2	--------
Zircon	Tr.	Tr.	Tr.	--------	Tr.	--------	Tr.
Muscovite	--------	Tr.	.5	--------	--------	--------	.6
Epidote	--------	--------	.8	--------	--------	--------	.1
Calcite	--------	--------	.1	--------	--------	--------	--------
Red iron oxide	--------	--------	--------	--------	--------	.3	5.6
Total	100.0	99.2	99.6	100.1	100.1	100.0	100.4

1. Granodiorite (specimen T6), near eastern contact of large body, 3 miles southwest of Mineral Hill.
2. Granodiorite (specimen T7), 1.7 miles southwest of Twin Buttes village.
3. Porphyritic granodiorite (specimen T9), 4 miles west of Mineral Hill.
4. Porphyritic granodiorite (specimen T10), McGee road, 4.7 miles west of Twin Buttes village.
5. Granodiorite (specimen T5), dump from shaft three-fourths of a mile north-northeast of Twin Buttes village.
6. Quartz monzonite facies of granodiorite (specimen T11), 1 mile northwest of Twin Buttes village.
7. Granophyric granodiorite porphyry (specimen T12A), small body near its contact with arkose, 2.4 miles southwest of Helmet Peak.

N. 5°–10° W. in what appears to be a conjugate set of fractures. Irregular bodies of aplite as large as 1,750 by 1,000 feet are found near the Esperanza mine.

Most of the aplite is a fine- to medium-grained granular aggregate of potassium feldspar, quartz, sodic plagioclase, and a little muscovite and biotite. The largest bodies near the Esperanza mine are relatively high in biotite and contain euhedral to subhedral phenocrysts of feldspar. The pegmatites, which are coarse-textured equivalents of the aplites, locally contain a little beryl and black tourmaline.

QUARTZ MONZONITE PORPHYRY

Quartz monzonite porphyry of premineralization age crops out in and near the Esperanza mine, in the Pima mine, and at a few other places. Similar premineralization porphyries are reported at depth near the Mission deposit (Richard and Courtright, 1959, p. 202) and near Mineral Hill (F. D. MacKenzie, 1959, oral communication). The occurrence of the same type of porphyry near several ore deposits in the district suggests that this type of porphyry and ore are genetically related.

The quartz monzonite porphyry is probably younger than the granodiorite. West of the Esperanza mine, a dikelike body of the porphyry cuts the Cretaceous (?) complex and extends a short distance into somewhat atypical granodiorite. North of the Esperanza mine, typical granodiorite contains several small dikes of what appears to be a fine-grained phase of the porphyry. These dikes certainly intrude the granodiorite, but their correlation with the porphyry must be tentative until thorough petrographic studies have been made. No indication of relative age was found along most of the contacts of the quartz monzonite porphyry and the granodiorite; these contacts are sharp at some places and apparently gradational at others.

Hand specimens of unaltered quartz monzonite porphyry are light to pinkish gray. Phenocrysts of pink potassium feldspar, white plagioclase, gray quartz, and black biotite are readily discernible in a very fine grained gray groundmass. Some of the potassium feldspar phenocrysts are as much as 10 by 20 mm, but most are 5 to 10 mm in maximum dimension. The phenocrysts of plagioclase, quartz, and biotite are distinctly smaller and commonly range from 1 to 5 mm in maximum dimension. The groundmass is a holocrystalline aggregate of grains 0.03–0.06 mm in diameter. Some of the plagioclase and biotite phenocrysts are only slightly larger than the groundmass grains.

The plagioclase phenocrysts are slightly zoned oligoclase, about An_{25}, with thin albitic rims. The potassium feldspar is perthitic and is presumably orthoclase, as it lacks visible quadrille twinning characteristic of microcline. The groundmass is essentially potassium feldspar and quartz; some plagioclase is present, but it is not twinned and is difficult to recognize. Modal analyses (table 2) indicate that the rock lacks sphene and contains a higher proportion of potassium feldspar than the granodiorite.

Texture is more useful than mineral composition in distinguishing the quartz monzonite porphyry from the granodiorite in the field. The typical quartz monzonite porphyry is characterized by an abundant fine-grained groundmass and conspicuous resorbed and rounded phenocrysts of quartz. The only part of the granodiorite that has a fine-grained groundmass is the porphyritic facies. The groundmass of granodiorite porphyry is rarely abundant enough to completely surround individual phenocrysts as it commonly does in the quartz monzonite porphyry. Rounded quartz eyes, which resemble the resorbed phenocrysts of the quartz monzonite porphyry, are found in some parts of the granodiorite, but they are generally accompanied by other quartz grains that lack this characteristic shape.

TABLE 2.—*Modal analyses of quartz monzonite porphyry*

	1 (*percent*)	*2* (*percent*)
Phenocrysts:		
Plagioclase	31	29
Orthoclase perthite	[1] 5. 5	17
Quartz	4. 7	14
Biotite and chlorite	4. 2	1. 3
Opaque minerals	1. 0	. 8
Apatite	Tr.	. 3
Epidote, red iron oxide, and zircon	. 4	. 1
Total	47	63
Groundmass:		
Potassium feldspar	27	22
Quartz	23	15
Plagioclase	[2] 3. 0	(2)
Total	53	37

1. Quartz monzonite porphyry (specimen T15), 0.6 mile northwest of the Esperanza (Duval) mine.

2. Quartz monzonite porphyry (specimen T16), 0.7 mile north of the Esperanza (Duval) mine.

[1] Phenocrysts of potassium feldspar make up 10 to 20 percent of the hand specimen from which this thin section was cut.

[2] Groundmass plagioclase is not twinned and is therefore difficult to distinguish from other groundmass constituents.

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RHYOLITIC TUFF

Rhyolitic tuff, which postdates the Cretaceous(?) complex and predates the Helmet fanglomerate, is exposed southeast and east of Helmet Peak (pl. 1). Paleozoic and Cretaceous(?) rocks are exposed northwest of the area of outcrop, and the Helmet fanglomerate is exposed south of it. The contact of the tuff with an andesitic unit of the Cretaceous(?) complex is exposed at one place and is evidently an unconformity. The tuff overlies andesite on an irregular surface that dips steeply south, and the lower part of the tuff contains large fragments of the andesite. The contact of the tuff with the Helmet fanglomerate also dips steeply to the south. The tuff is soft and friable near the contact. A few fragments of the tuff were found in the lower part of the fanglomerate.

The typical rhyolitic tuff is grayish pink to grayish orange and is well indurated. Hand specimens consist of crystals and fragments of glassy feldspar, quartz, and biotite as much as 2 mm in diameter, and larger lithic fragments, embedded in a glassy-looking matrix. Most of the lithic fragments are of rhyolitic rock and are regarded as accessory; that is, they are believed to be fragments of previously consolidated volcanic rock torn from the volcanic vent by the same eruption that yielded the juvenile constituents of the tuff. Some are accidental fragments from the Cretaceous(?) complex.

In thin section, the typical tuff is seen to be a welded crystal tuff. Crystals and angular fragments of plagioclase, sanidine, quartz, and biotite are embedded in a matrix of compacted glass shards and pumice fragments, now partly devitrified. Because the plagioclase grains are andesine (An_{30-35}) and are relatively abundant (analysis 1, table 3) the rock may have the chemical composition of dacite or rhyodacite rather than rhyolite.

TABLE 3.—*Modal analyses of rhyolitic tuff and tuffaceous sandstone*

	1 (*percent*)	*2* (*percent*)
Plagioclase	23	34
Sanidine	4.8	2.3
Quartz	8.7	21
Biotite	2.7	1.7
Opaque minerals	.7	1.5
Apatite	Tr.	----
Lithic fragments	13	11
Calcite	----	1.0
Matrix	47	27

1. Rhyolitic crystal tuff (specimen T37), one-half a mile south of Helmet Peak.
2. Tuffaceous sandstone bed in Helmet fanglomerate (specimen T51), about 3 miles southwest of Helmet Peak.

Included with the rhyolitic tuff on the geologic map is a small isolated outcrop of pale-red lapilli tuff, petrographically different from the typical tuff. The pale-red tuff consists of angular fragments of devitrified volcanic rock that contains phenocrysts of altered feldspar and biotite, in a fine-grained clastic matrix of essentially the same composition. There are a few angular chips of quartz in the matrix. The red is due to disseminated hematite dust, which is sparse in the fragments and more abundant in the matrix. Typical rhyolitic tuff is exposed on three sides of the lapilli tuff.

The rhyolitic tuff is younger than the post-Cretaceous(?)-pre-Helmet orogeny, for it truncates the Helmet Peak anticline and the faults that cut the limbs of this fold (pl. 1). The tuff is not found in contact with any of the upper Cretaceous or lower Tertiary intrusive rocks; therefore, the relative age of tuff and intrusive rocks is indeterminate.

Whether the tuff is premineralization or postmineralization is not clear. Diamond-drill holes through the alluvium east of Helmet Peak indicate that the tuff, or some other unit that is indistinguishable from it in hand specimen, is altered and metallized. On the other hand, surface evidence suggests that the tuff may be postmineralization; exposures of the typical tuff are unaltered, and beds of similar tuff are found in the overlying Helmet fanglomerate, which is clearly postmineralization. (See table 3.)

HELMET FANGLOMERATE

NAME

A deformed postmineralization conglomerate exposed near the center of the Pima district is here named the Helmet fanglomerate, for Helmet Peak, a conspicuous landmark less than a mile north of the area in which the fanglomerate is exposed. The stratigraphy of the fanglomerate must be inferred from scattered outcrops; therefore, the formation has no type section in the ordinary sense. The most nearly continuous exposures are along a north-trending line from a point three-fourths of a mile southeast of Helmet Peak to a point 1¼ miles north-northwest of Twin Buttes village. (See pl. 1.)

GENERAL FEATURES AND GEOLOGIC RELATIONS

The Helmet fanglomerate is predominantly a coarse ill-sorted conglomerate characterized by angular pebbles, cobbles, and boulders in an abundant silty matrix. The color ranges from dusky red and red brown in the lower part of the formation to light yellowish gray in the upper part. In most outcrops the fanglomerate is no more consolidated than the Recent alluvium. Drilling data indicate that parts of the formation are moderately well indurated at depth.

Fragments in the fanglomerate have been derived from various Paleozoic formations, from the Cretaceous(?) sedimentary and volcanic rocks, intrusive porphyries, and the granodiorite. Some fragments of Paleozoic and Cretaceous(?) rocks are metamorphosed and copper stained. The proportion of the various rock types is not constant, and in some beds nearly all the fragments are of the same rock type.

The fanglomerate contains concordant lenses of rigorously monolithologic breccia, and to the west it interfingers laterally with such breccias. Where exposures are best, the breccia masses seem to be stratigraphic units of the Helmet emplaced as landslide blocks while the fanglomerate was accumulating. Some of the bodies tentatively interpreted in this way, and therefore assigned to the Helmet, are very large and lie at and near the base of the formation (pl. 1). These masses are partly surrounded by fanglomerate and might represent pre-Helmet hills that were buried by the fanglomerate, or they might have been emplaced by unknown intra-Helmet or post-Helmet faulting.

Andesite lava flows and rhyolitic tuffs and tuffaceous sediments are intercalated with the fanglomerate. The andesite flows are found in the lower part of the formation (pl. 1). The rhyolitic tuffs and tuffaceous sediments are dispersed as thin units higher in the formation; these units are not shown on the map because of scale limitations.

Bedding in the fanglomerate is generally obscure, but here and there changes in color, texture, and composition are sufficiently abrupt to permit measurement of the dip and strike (pl. 2). The tuff and tuffaceous sediments are generally in distinct beds. A total of 28 bedding measurements have been made. Statistical analysis of these data by graphic means reveals a nearly uniform strike of N. 60° E. and dip of 56° SE. (See fig. 16.) Strata in the upper part of the formation have the lowest dips and greatest variation in strike.

Unquestionably there would be more scatter in the bedding attitudes if more data were available and if observations were uniformly distributed geographically. Though observations were made in nearly all parts of the outcrop area, some of the observations are clustered where bedding is distinct, and the results are biased thereby. Nevertheless, the general conclusion that the formation dips moderately steeply to the southeast seems to be well substantiated and is confirmed by the preferred orientation of flat fragments in the fanglomer-

HELMET FANGLOMERATE

Outcrop showing steeply inclined bedding planes and a disturbed layer interpreted as a mudflow filling a shallow channel.

HELMET FANGLOMERATE SHOWING FRACTURED AND FAULTED BOULDERS

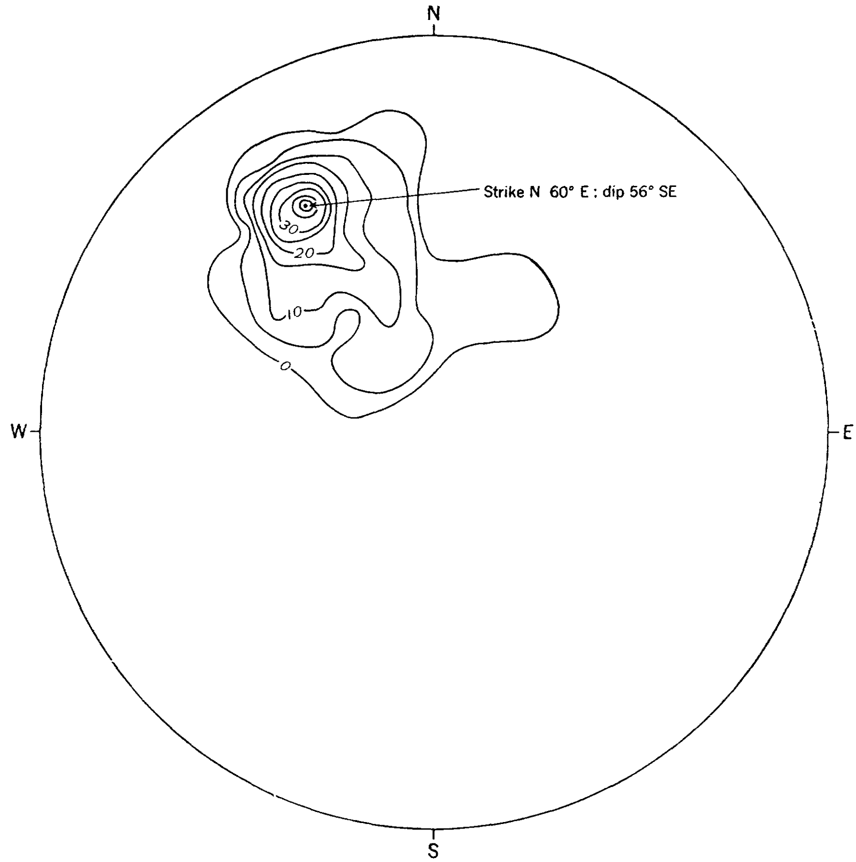

FIGURE 16.—Contour diagram of poles of 28 bedding planes in Helmet fanglomerate. Equal-area projection of lower hemisphere. Contoured at 0, 5, 10, 15, 20, 25, 30, 35, and 40 percent.

ate at many places where bedding attitudes cannot be measured precisely.

Along its northwest side, the Helmet fanglomerate is in depositional contact on the rhyolitic tuff and probably on the Cretaceous(?) rocks. To the northeast it extends beneath Quaternary alluvium at least 4 miles as shown by drill holes. The other boundaries are fault contacts with Precambrian granite, Paleozoic sedimentary rocks, and granodiorite. The consistent southerly dip of the fanglomerate indicates that the fault or faults on the south must have large displacement. The interpretation herein suggested is that the southwestern, southern, and southeastern boundaries are defined by the low-dipping San Xavier thrust, offset at one place by a steep north-trending fault called the Ruby fault.

LITHOLOGY

The lithology and distribution of rocks of the Helmet fanglomerate will be described in this section, particularly the aspects that bear on origin and stratigraphic sequence.

CONGLOMERATES

The conglomerates, which make up most of the formation, are generally coarse, ill sorted, and poorly bedded. Most of the fragments are angular to subangular, although a few well-rounded pebbles, evidently second-generation pebbles from Cretaceous(?) conglomerate units, were found near the base of the formation. At some places, pebbles, cobbles, and boulders were fractured and faulted slightly after deposition (pl. 3).

Variations in color, lithology of fragments, and sedimentation features indicate three gradational stratigraphic units: (a) a lower red unit that underlies a zone of andesite flows, (b) an intermediate, generally brown unit that overlies the andesite flows and contains lentils of monolithologic breccia and thick nearly monolithologic conglomerate beds, and (c) an upper light-gray unit that forms the highest part of the formation exposed. (See pl. 1.)

The lower red unit ranges in color from dusky red and dark reddish brown to pale reddish brown and locally brownish gray. It is the most consistently unstratified part of the formation though its general southeast dip is commonly revealed by the preferred orientation of tabular fragments and by ill-defined variations in texture. Some fragments are as much as 5 feet in diameter, but relatively few are above cobble size. Most are of Cretaceous(?) arkose. Fragments of porphyry, including Cretaceous(?) rhyolite and andesite, are generally present and are abundant locally. Granodiorite fragments are scarce, and no fragments from Paleozoic or Precambrian formations have been noted.

Parts of the red unit are exposed in the northern two-thirds of the Helmet fanglomerate preserved west of the Ruby fault. Here the red unit is more consolidated than east of the fault; it contains lentils of monolithologic breccia and interfingers with such breccias to the west (pl. 1). Rock types in the breccia are particularly abundant as fragments in the immediately adjacent conglomerate. For example, granodiorite fragments are fairly abundant near a lentil of granodiorite breccia but were not found elsewhere in this area; where the conglomerate interfingers with Cretaceous(?) monolithologic rhyolite breccia, about half of the fragments in the conglomerate are like the rhyolite in the adjacent breccia.

The brown unit, which overlies the andesite flows, has more diverse lithology than the red unit. Light- to moderate-brown conglomerate is abundant and contains red, gray, yellowish-gray, and greenish-gray beds. Thin layers of tuff and tuffaceous sediments are present, as are monolithologic-breccia lentils of Paleozoic and Cretaceous(?) rocks. The fragments in the conglomerates are mostly from the Cretaceous(?) complex, but some are of granodiorite and Paleozoic rocks, including copper-stained tactite. Scarce fragments of the underlying andesite flows are present.

More conglomerates of the brown unit are monolithologic toward the southwest. The part of the unit west of the Ruby fault is composed almost entirely of fragments of Cretaceous(?) volcanic rocks. Exposures are poor, but float indicates that rhyolitic and andesitic types predominate in alternate layers tens of feet in thickness. East of the Ruby fault, some conspicuously monolithologic conglomerate units are found in the southern part of sec. 23 and the southwestern part of sec. 24, T. 17 S., R. 12 E.

The brown unit grades upward into a gray unit which is the highest part of the formation exposed. The conglomerates in the gray unit range from very light gray to grayish yellow, grayish orange pink, and light brown. Their fragments are of all types found in the lower units. Some tendency toward monolithologic composition was noted southwest of the Ruby Star Ranch, where small and large fragments of granodiorite constitute as much as 50 percent of the total, and no fragments of Paleozoic rocks were noted.

The gray unit, which is confined to the block east of the Ruby fault, contains sparse thin beds of tuff, and also of poorly consolidated sandstone, siltstone, and bedded conglomerate. Some masses of brecciated Paleozoic limestone occur along and near the San Xavier thrust, which cuts off the unit to the south. The easternmost and largest of these masses is probably a landslide block.

ANDESITE FLOWS

Tabular bodies of distinctive porphyritic andesite crop out within a thin zone in the lower middle part of the Helmet fanglomerate (pl. 1). These bodies are regarded as lava flows rather than as intrusive bodies because they appear to be rigorously concordant, they have red vesicular tops, and fragments of the andesite are found as boulders in the overlying fanglomerate. The macroscopic characteristics of a typical flow are given in the following section measured several hundred yards west of the Twin Buttes road:

	Feet
Recent alluvium.	
Unconformity.	
Andesite flow, porphyritic, about 35 percent large (5- to 25-mm) tabular phenocrysts of plagioclase, and 5 percent small (1- to 5-mm) phenocrysts of pyroxene or serpentinous pseudomorphs thereafter, in aphanitic groundmass. The groundmass is medium light gray in the lower third and grades upward to dusky red and moderate reddish brown at top. Vesicles appear near middle and become more abundant upward. Many vesicles are filled with quartz and a green mineral, probably celadonite	257
Helmet fanglomerate, grading upward from brownish gray to dusky red, exposed	75

As seen in thin section the plagioclase phenocrysts are weakly zoned labradorite (An_{50-60}). They contain irregular inclusions of groundmass material and scarce inclusions of pyroxene. Parts of many plagioclase crystals have anomalous undulatory extinction. The pyroxene phenocrysts are augite and hypersthene; some specimens lack hypersthene but contain patches of olive high-birefringent serpentinous material presumed to be pseudomorphs after that mineral. There are also microphenocrysts of magnetite. The groundmass consists of microlites of plagioclase, minute pyroxene grains, and partly devitrified interstitial glass. Opaque magnetite dust occurs in the gray facies and red hematite dust in the red facies. The plagioclase microlites are too small for satisfactory determination but are probably andesine, or possibly oligoclase. The apparent average composition of the plagioclase is in the andesine range, and therefore the rock is classified as andesite.

The andesite mapped west of the Ruby fault, in sec. 22, T. 17 S., R. 12 E., is a somewhat schistose medium-dark-gray porphyritic rock containing plagioclase phenocrysts ¼–¾ inch in length. Locally it contains amygdules of quartz. The plagioclase phenocrysts are a sodic variety and are embedded in a foliated granoblastic groundmass of biotite, quartz, and alkalic feldspar. Correlation of this rock with the normal andesite is tentative and is based entirely on the gross textural characteristics. The foliation can be interpreted as a frictional effect of post-Helmet thrusting, but no explanation of the probable increase in alkali content can be suggested. The body mapped is the largest of several masses of similar rock within and adjacent to the fanglomerate in this area. The structural relations of these masses are obscure.

Tertiary lava flows that are megascopically like the typical andesite in the Helmet fanglomerate are widely distributed in southeastern Arizona. About 25 miles northeast of the Pima district, two zones have been reported in the Pantano formation of Brennan.[2] Flows also occur at the south end of the Tucson Mountains and far to the northeast in the Galiuro and Winchester Mountains and at the south end of the Pinaleno Mountains (fig. 15). Dikes that appear to be of similar rock are of even wider occurrence.

RHYOLITIC TUFFS AND TUFFACEOUS SEDIMENTS

Sparse units of rhyolitic tuff and tuffaceous sediments occur in the Helmet fanglomerate stratigraphically above the zone of andesite flows. Crystal, lithic, and argillized vitric varieties are represented. Some tuffaceous units evidently represent unmodified ash falls, and others have been reworked by running water and contain admixed material that is not of pyroclastic origin.

The beds of tuff and tuffaceous sediments are generally only a few inches to a few feet thick. Individual beds are erratically dispersed in the conglomerate or are concentrated in zones a few tens of feet thick. Units 2 to 6 of the following section constitute the thickest tuffaceous zone found.

Section of tuffaceous zone in Helmet fanglomerate SW1/4SW1/4 sec. 22, T. 17 S., R. 12 E.

	Feet
1. Conglomerate(?), covered by soil and rubble; rubble predominantly Cretaceous(?) rhyolite and andesite	73
2. Sandstone, tuffaceous, pale-red, very fine to fine-grained, fairly well sorted, unbedded, well-cemented; characterized by small (mostly 0.05- to 0.1-mm) angular chips of quartz, plagioclase and biotite, and abundant fragments of felsic volcanic rock as much as 2 mm long: contains about 5 percent granules and pebbles of rhyolite, porphyry, felsite, and argillized pumice(?)	5.6
3. Sandstone, pebbly, clayey, tuffaceous, yellow-gray, very fine to fine-grained, unbedded, poorly cemented and easily eroded; composed of fragments of quartz, feldspar, biotite, and devitrified glass (?) in matrix (as much as 25 percent) of clay that swells on hydration and is probably devitrified ash; contains scattered angular granules and pebbles of porphyry; grades into bed below	16.3
4. Sandstone, pebbly, tuffaceous, grayish-orange-pink, fine- to medium-grained, poorly sorted, unbedded, well-cemented; composed of fragments of quartz, feldspar, biotite, and rock chips; angular granules and pebbles make up 10–20 percent	1.6
5. Sandstone, clayey, tuffaceous, yellowish-gray to white, fine- to medium-grained, poorly sorted, unbedded, poorly cemented and easily eroded; composed of fragments of quartz, feldspar, biotite, and divetrified glass (?) in matrix (about 10 percent) of clay that swells on hydration and probably is devitrified ash	11.7
6. Sandstone, tuffaceous, grayish-pink, medium- to coarse-grained, poorly sorted, laminated to very thin bedded, firmly cemented; composition given as analysis 2, table 3	3.9

[2] Brennan, D. J., 1957, Geological reconnaissance of Cienega Gap, Pima County, Arizona: Arizona Univ. Ph. D. thesis (ms. on file at Univ. Arizona library), p. 14, 22.

	Feet
7. Conglomerate, grayish-red; composed of angular fragments of Cretaceous(?) rhyolite, andesite, and quartzite in abundant silt-rich matrix; largely covered by soil and rubble; rubble about 80 percent Cretaceous(?) rhyolite	12
Total thickness measured	124.1

In general, the crystal and lithic tuffs are well-indurated sandy-textured rocks, which range from yellowish gray through grayish orange pink to pale red. Crystals and fragments of quartz, feldspar, and biotite, and rock chips are distinguishable in hand specimens. The rock fragments, which range from sand to pebble size, are predominantly of felsic volcanic rock including argillized pumice (?). Some are accidental fragments of the pre-Helmet formations.

The mineral fragments in the tuff, in order of abundance, are plagioclase (between oligoclase and andesine), quartz, sanidine, biotite, and opaque material. The mineral grains and associated rock fragments are embedded in a matrix of dust or clay of unknown composition. The mode of a reworked crystal tuff is given as analyses 2, table 3. Rock of this type grades into lithic vitric, and mixed varieties by variation in the proportion of the main contituents.

The commonest units of volcanic derivation are beds of bentonitic clay or sandy clay regarded as argillized vitric tuff. These units are associated with the crystal and lithic tuffs and are found also as isolated beds in the conglomerate. The clay layers are light gray to yellowish gray. Their exposed surface is characteristically crackled as a result of swelling on hydration. Veinlets of quartz are common along bedding planes and crosscutting fractures. These veinlets probably represent silica released from the volcanic glass when it was argillized. The microscopic characteristics of the rock are not known, as no specimens found were sufficiently coherent to cut and grind for microscopic study.

MONOLITHOLOGIC BRECCIAS

The lenses and tongues of breccia here interpreted as part of the Helmet fanglomerate characteristically consist of recemented breccia derived from a single pre-Helmet formation. Some breccia bodies consist of parts of two or more formations (pl. 1). In many parts of the breccia, it is clear that individual fragments have moved by rotation and translation with little if any churning movement. Formational contacts and even small-scale features like individual beds can be traced through intensely brecciated rock. To preserve these primary features, the entire mass of breccia must have been emplaced in essentially one piece. Landslides are probably the principal emplacement mechanism.

A landslide origin is best established for thin lentils wholly surrounded by conglomerate. The largest and best exposed of these lentils forms a low ridge 1½ miles south-southeast of Helmet Peak. This lentil is a few feet to about 200 feet wide and at least 3,500 feet long. The total length is not known as the eastern end is concealed by alluvium. The lentil is composed of brecciated and recemented beds of the Scherrer formation and the Concha limestone. The contacts between individual beds and between the two formations are still discernible and are parallel to the long axis of the lentil. The breccia fragments are rarely more than a few inches in diameter. Both contacts of the lentil are exposed and dip southeast parallel to bedding in the conglomerate. Although minor slippage may have taken place along the contacts, there is no evidence of large fault movement.

Other thin lentils of brecciated Paleozoic and Cretaceous (?) rocks and of granodiorite are found in the fanglomerate, but many of these lentils are too poorly exposed to map. Boulders of the same rock type that makes up the lentil are commonly abundant in the conglomerate on strike with the lentil, suggesting that the lentil was emplaced while the conglomerates were accumulating. The only alternative to contemporaneous emplacement, emplacement by post-Helmet faulting, is improbable. The concordance of the lenses and their small to moderate size and wide geographic and stratigraphic dispersal are difficult to explain by faulting. Furthermore, stratigraphic markers in the fanglomerate, such as the andesite flows and the lower red unit, are not repeated as one would expect if post-Helmet faulting had been involved.

Concordant tabular masses of monolithologic breccia that resemble the lentils just described have been reported from many localities in and on the valley-fill deposits of northern Arizona, southern Nevada, and southern California. In all the descriptions that I have found, the breccia masses have been interpreted as contemporaneous in origin with the deposits that contain them. Some have been interpreted as remnants of thrust plates that rode on the surface and as huge blocks that were shoved by such thrust plates (Longwell, 1949, p. 935, 947–50). Others have been interpreted as landslides, some of which moved 5 miles or more from their source (Woodford and Harriss, 1928, p. 279–290; Noble, 1941; Jahns and Engel, 1949, 1950; Longwell, 1951). The recent slides evidently broke off active fault scarps (Longwell, 1951) and off thrust plates that were moving on the surface (Woodford and Harriss, 1928, p. 289–90). The source of the older slides is obscure.

The thin lentils in the Helmet fanglomerate are similar to each other and probably have a similar origin. None of them is thick enough to transmit the force necessary to have shoved it into place.

If there were only one lentil, one might suppose that it was part of a much thicker thrust plate that was eroded before burial. To assume many thrust plates all deeply eroded before burial is to stretch geologic probability beyond its limits. The most likely interpretation is that the lentils represent landslides.

The monolithologic breccias here assigned to the Helmet fanglomerate (pl. 1) include some large masses of breccia for which a landslide origin is only tentatively suggested. Near the base of the formation are large outcrops of arkose and granodiorite breccia. The distribution of these outcrops suggests that they are parts of a single body of breccia 10,000 feet long and as much as 4,000 feet wide, offset by the Ruby fault. At both ends, the body appears to lie within the red unit of the fanglomerate. In lithology, shape, and apparent geologic relations, the body resembles the probable landslide block in the SW¼ sec. 23, T. 17 S., R. 12 E. Furthermore, it appears to be out of place with respect to the pre-Helmet rocks to the north.

Interpretation of the large body as a landslide block is doubtful because it is less thoroughly brecciated than smaller landslide bodies, and some of the brecciation was pre-Helmet; it is unusually large for a landslide; and it lies so near the bottom of the Helmet that it can be interpreted as part of the basement on which the fanglomerate was deposited. In the NW¼ sec. 22, T. 17 S., R. 12 E., unbrecciated granodiorite cuts arkose breccia. In a contact hornfels zone several feet wide, the breccia has been healed by recrystallization and contains porphyroblasts of biotite and alkalic feldspar. The brecciation at this locality was older than the granodiorite, and does not indicate structural disturbance during Helmet time. If the body was emplaced as a single landslide block, this block was at least 10,000 feet long and 3,300 feet thick. Landslides of such dimensions are difficult to comprehend but probably could take place in front of large fault scarps or thrust plates moving on the surface. The mass could be a composite of several slides, but no field evidence suggesting this has been recognized.

Possibly the large outcrops of arkose and granodiorite breccia are not part of the Helmet fanglomerate but are part of the basement on which the fanglomerate was deposited. They could represent steep pre-Helmet hills that were buried by the fanglomerate; or they could have been emplaced by unrecognized intra-Helmet or post-Helmet faults.

In the SE¼ sec. 21, T. 17 S., R. 12 E., the red unit and part of the brown unit of the fanglomerate interfinger with thoroughly brecciated Cretaceous(?) rocks (pl. 1). The breccias are here interpreted as a composite of small landslides and possibly talus accumulations of Helmet age. The outcrops are poor, and some of the fingers could represent post-Helmet fault wedges. A great deal of brecciation and shearing is related in space to the San Xavier thrust, and some of the breccias tentatively assigned to the Helmet in this area are unquestionably thrust breccias, at least in part.

THICKNESS

The apparent thickness of the Helmet fanglomerate exposed south of Helmet Peak is about 10,500 feet. This section includes all parts of the formation exposed in the Pima district, but the section is faulted off at the top and therefore stratigraphically higher beds of unknown thickness and character are not represented.

No major faults duplicate the section, for the stratigraphic units—the red unit, andesite flows, brown unit, and gray unit—are not repeated. Major strike faults that cut out beds could exist, but none have been recognized. Small shear zones marked by concentrations of calcium carbonate cut the fanglomerate at some places, but neither the amount nor the direction of movement along them is known. Tiny faults offset some of the boulders (pls. 3 and 5, p. 97–98). Some of these faults would lead to overestimation and others to underestimation of the stratigraphic thickness. If the localities discussed on pages 97–98 are representative, the faulting would lead to slight overestimation, perhaps by 2 or 3 percent.

ORIGIN

The Helmet fanglomerate probably formed as fan deposits near the base of a tectonically active mountain mass. The predominant conglomerate facies is ill sorted, ill bedded, and characterized by angular to subangular fragments, suggesting rapid deposition near the source. The largest boulder found measured 8 by 7 by 4 feet and was evidently larger originally, for fragments recently broken from it littered the arroyo channel beneath the outcrop. A heterogeneous mixture of such large fragments with others as small as granules, all in an abundant fine-grained matrix, suggests emplacement as mudflows. The nearly monolithologic conglomerate units can be interpreted as mudflows or torrential stream deposits of localized source, and possibly as a result of interfingering of material from adjacent drainage channels.

Sedimentary structural features that might reveal the direction from which the material was carried are very scarce in the conglomerates. No crossbedding was found. At one locality, obscure imbrication suggests movement from the west, but in general the formation is too poorly bedded to determine whether the arrangement of the fragments is imbricate. Two shallow filled channels were found, which plunge S. 40° W. and S. 5° W., respectively. (See pl. 2.) If the bedding at the two localities is restored to an assumed original horizontal position by rotation about an axis parallel to the strike, the two channels trend S. 30° W. and S. 3° W., respectively. These few data suggest a source to the west or southwest.

While the conglomerates were accumulating, great masses of rock occasionally broke from the tectonically mobile source area and slid down the fan surface. These landslide blocks were buried by conglomerate and now appear as lentils and tongues of monolithologic breccia.

At one stage, porphyritic andesite lavas were poured out over the fan surface. Slightly later, thin interbeds of tuff and tuffaceous sediment were deposited as a result of explosive and probably more distant eruptions of rhyolitic rock.

The distribution of landslide material and the regional variations in the texture and composition of the conglomerates tend to confirm that the source area was to the west, and probably not far away. Landslides make up an increasing proportion of the formation toward the west; this increase strongly suggests a nearby source in that general direction. Tongues of breccia in the westernmost exposures could even represent ancient talus accumulations. A greater proportion of the conglomerates are monolithologic toward the west, and this further suggests a western source. In drill holes that have penetrated the formation northeast of its area of outcrop, the conglomerates are generally finer textured than those exposed. Evidently the source was to the west, but whether to the southwest, west, or northwest is not revealed by these data.

AGE AND CORRELATION

The only fossils that have been found in the Helmet fanglomerate are in boulders and breccia fragments, and are of Paleozoic age. Obviously these fossils indicate the age of the source rocks. Conclusions regarding the age of the fanglomerate must depend on lithology, geologic relations, and correlation with formations that can be dated by direct evidence.

The fanglomerate is younger than the ore deposits of the district and older than a subsequent orogeny. The fanglomerate contains boulders of the Late Cretaceous or early Tertiary intrusive bodies and of altered and mineralized Paleozoic and Cretaceous(?) rocks, indicating that these rocks were in existence and had been exposed by erosion at the time the fanglomerate was deposited. The fanglomerate now dips steeply and is cut by large faults, one of which, the San Xavier thrust, is of regional importance. The beds strike east-northeast at a large angle to the younger Basin-and-Range trend, which is northwest. The overall geologic relations suggest the fanglomerate is of middle Tertiary age.

The Helmet fanglomerate almost certainly correlates with the Pantano formation of Brennan,[3] which has its type section about 25 miles southeast of Tucson. This formation is described as a thick deformed sequence of conglomerate, sandstone, siltstone, mudstone, and scarce argillaceous limestone, with intercalated andesite flows which are lithologically like the flows in the Helmet. The pebbles and boulders are predominantly of Cretaceous(?) arkose, sandstone, and volcanic rocks. Boulders of Paleozoic limestone also are present. Schwalen and Shaw (1957, p. 15–22) present evidence that beds like the Pantano probably underlie the central part of the Santa Cruz valley beneath the cover of younger alluvial deposits. The data suggest that the Helmet and Pantano are essentially contemporaneous and are continuous beneath the younger valley fill. The Helmet evidently was deposited nearer the source than the Pantano.

In the San Pedro valley south of Redington (fig. 15), deformed fan deposits have yielded a lower Miocene rhinoceros. These beds resemble the Pantano lithologically and are cut by dikes of andesite macroscopically identical with the flows in the Pantano formation and Helmet fanglomerate. Boulders of the andesite in beds associated with the deformed fan deposits south of Redington suggest that andesite and these fan deposits are nearly contemporaneous (John F. Lance, 1958, oral communication). Tentative correlation of the Pantano, the Helmet, and the deformed fan deposits seems justified. If this correlation is correct, the Helmet fanglomerate is of early Miocene age.

ROCKS YOUNGER THAN THE HELMET FANGLOMERATE

ANDESITE DIKES

A narrow zone of andesite dikes extends from a point half a mile north of Twin Buttes village for about 2¾ miles to the north-northwest parallel to the Ruby fault (pl. 1). The principal dikes, which are a few tens of feet wide, strike north to northwest and are nearly vertical. One dike strikes N. 70° E., perpendicular to the general trend. A lentil of monolithologic breccia in the Helmet fanglomerate is not offset where it is cut by a dike, which indicates little if any fault movement in the dike zone. The dike fissures and the dikes are probably younger than the San Xavier thrust and the tilting of the Helmet fanglomerate, for no offset in the dike zone is apparent along the thrust.

[3] Brennan, D. J., 1957, Geological reconnaissance of Cienega Gap, Pima County, Arizona: Arizona Univ. Ph. D. thesis (ms. on file at Univ. Arizona library), p. 14–22.

A typical dike is well exposed in an arroyo in the SW¼SE¼ sec. 13, T. 17 S., R. 12 E. This dike strikes N. 17° W. and dips 87° E. and is 40 feet wide. The adjacent fanglomerate is distinctly reddened for several feet from the dike, evidently as a result of baking. The dike magma was intruded almost directly upward, for phenocrysts and flat elongate vesicles have a planar flow structure parallel to the dike walls and a linear flow structure that plunges down the dip. The dike is jointed parallel to the walls, and also in transverse columns.

As seen in hand specimen, the dike rock is a light-brownish-gray porphyry with a purplish cast. Phenocrysts several millimeters across of feldspar, hornblende, and a little biotite are embedded in a fine-grained felsic groundmass.

As seen in thin section, the feldspar phenocrysts are plagioclase which is zoned from about An_{63} at the cores to about An_{35} at the rims and probably averages andesine An_{45-50}. Other phenocrysts are of hornblende, deep-brown biotite, opaque grains, and a little apatite and zircon. The groundmass consists mostly of oligoclase microlites (probably An_{10-20}), biotite shreds, minute opaque grains, and interstitial partly devitrified glass. The groundmass plagioclase and biotite are oriented by flow. The modal analysis of a thin section of the rock is given in table 4.

TABLE 4.—*Modal analysis of post-Helmet andesite dike*

	Percent
Phenocrysts:	
Plagioclase (An_{35-65})	18
Hornblende	4.2
Biotite	.6
Opaque minerals	.7
Apatite	Tr.
Zircon	Tr.
Total	23
Groundmass:	
Plagioclase ($An_{10-20?}$)	[1] 25
Biotite	3.7
Hornblende	.8
Opaque minerals	1.5
Partly devitrified glass	46
Total	77

[1] Includes a little low-birefringent material in tiny irregular grains, possibly quartz or potassium feldspar.

ALLUVIUM

The only other post-Helmet unit in the map area (pl. 1) consists of fan, terrace, and pediment gravel and of Recent alluvium in stream channels. All these deposits, which are shown as alluvium on the geologic map, are composed of debris from older formations in the district. They overlie the Helmet fanglomerate and post-Helmet dikes unconformably and have nearly horizontal bedding.

Areas of alluvium were not mapped where scattered bedrock outcrops permitted confident inference of the bedrock geology. As a result, many areas shown as bedrock are actually concealed in part by thin tongues and patches of alluvium. The intricate alluvium-bedrock relations shown in the latitude of the Helmet fanglomerate outcrops express detailed mapping of the alluvium in this area.

STRUCTURAL IMPLICATIONS OF THE FANGLOMERATE

The Helmet fanglomerate is younger than the ore and therefore may cover mineralized rocks. Available drill-hole data indicate that the fanglomerate extends far to the northeast beneath the alluvium.

The lithology of the fanglomerate and its geologic relations indicate that the Pima district has undergone two major orogenies since Cretaceous(?) time. The structural features of the Paleozoic and Cretaceous(?) rocks are complex and have a general northwest trend. Some of these earlier structural features are truncated by the Helmet fanglomerate, which trends northeast. The older northwest-trending structural features are older than the granodiorite and the ore. The post-Helmet structural features are younger than the ore. These two groups of structural features must be distinguished from one another to properly interpret the structural history. Some aspects of the post-Helmet structure are discussed in the following paragraphs as a contribution to this ultimate objective.

POST-HELMET ROTATION OF STRUCTURAL FEATURES

If the Helmet fanglomerate is in depositional contact on the older rocks to the north, as suggested by the geologic relations south of Helment Peak (p. 76), the tilting of the fanglomerate must have affected the structural features in the underlying block. To visualize the pre-Helmet geology properly, one must first remove the tilt. To make a complete restoration one must know the initial strike and dip of the Helmet fanglomerate, its present strike and dip, and what part or parts of the district were rotated with the fanglomerate.

The initial strike and dip of the Helmet fanglomerate can be estimated from the inclination of modern fans and the source direction of the Helmet. The fan surfaces studied by Blissenbach (1952) dip 6° to 10° at the apex and flatten rapidly downslope; the upper part of one fan merged into a talus slope with a maximum inclination of 15°. Inasmuch as the source of the Helmet fanglomerate was to the southwest, west, or northwest (p. 87–88), the initial dip was probably 10°

or less to the northeast, east, or southeast. Possibly the initial dip was as much as 25° in one or another of these directions.

The fanglomerate now exposed strikes about N. 60° E. and dips about 56° SE. (fig. 16). The area of outcrop is 3 miles long parallel to the strike and 2½ miles wide perpendicular to the strike. Clearly a large block of ground has been rotated, but how and when rotation took place is not known. If the rotation was related in origin to the San Xavier thrust, it was probably confined to the thrust plate and possibly confined to only part of the plate. If rotation was unrelated to the thrust and was either prethrust or posthrust, it was not so confined and may have affected much or all of the district. In any case, the rocks in the thrust plate immediately below the fanglomerate must have been rotated.

The Helmet Peak anticline lies a short distance structurally below the fanglomerate and was probably rotated to the same extent as the fanglomerate. The axial plane of this fold is now vertical and strikes about N. 25° W.; its plunge is about 60°, S. 25° E. Table 5 shows its pre-Helmet orientation under seven hypotheses as to the initial strike and dip of the Helmet fanglomerate. The restorations, made by stereographic projection (Bucher, 1944), are based on the least possible rotation that would restore present bedding planes of the fanglomerate to their initial attitude. The axis of rotation is the line of intersection of the present and initial planes, and the amount of rotation is the dihedral angle between these planes. In pre-Helmet time, the anticline trended a little more to the northwest than at present and plunged at a small to moderate angle to the southeast. The axial plane was probably still essentially vertical (first four restorations), but was overturned to the

TABLE 5.—*Rotation of the Helmet Peak anticline*

[Assuming that (1) the axial plane of the anticline is now vertical and strikes N. 25° W.; (2) its axis plunges 60°, S. 25° E.; (3) the Helmet fanglomerate now strikes N. 60° E. and dips 56° SE.; and (4) the initial strike and dip of the fanglomerate was that shown in the first column of the table]

Assumed initial strike and dip of Helmet fanglomerate	Least possible rotation to restore initial dip		Pre-Helmet orientation of Helmet Peak anticline	
	Plunge of axis of rotation and direction	Amount (clockwise as viewed from northeast)	Strike and dip of axial plane	Plunge of axis and direction
Horizontal	0°, N. 60° E.	56°	N. 28° W., 86° NE.	4°, S. 28° E.
Due north, 10° E	9°, N. 66° E.	52°	N. 32° W., 87° SW.	9°, S. 31° E.
N. 45° W., 10° NE	9°, N. 66° E.	60°	N. 33° W., 85° SW.	2°, S. 33° E.
N. 45° E., 10° SE	3°, N. 62° E.	46°	N. 28° W., 89° NE.	14°, S. 28° E.
Due north, 25° E	24°, N. 78° E.	47°	N. 39° W., 76° SW.	18°, S. 35° E.
N. 45° W., 25° NE	22°, N. 76° E.	65°	N. 40° W., 69° SW.	3°, S. 39° E.
N. 45° E., 25° SE	10°, N. 67° E.	33°	N. 30° W., 87° SW.	28°, S. 29° E.

northeast if the fanglomerate had a very steep initial dip (last three restorations).

If the same restorations that were applied to the Helmet Peak anticline are applied to other structural features, some of the results are surprising. For example, the high-grade ore body in the Pima mine and a large premineralization fault now strike about N. 80° E. and dip about 50° S. (Thurmond and Storms, 1958, p. 5–8); the same rotations that were applied to the Helmet Peak fold yield the following results:

Assumed initial strike and dip of Helmet fanglomerate	*Indicated pre-Helmet strike and dip of Pima ore body*
Horizontal	N. 2 ° W., 16° W.
Due North, 10° E	N. 15° W., 8° SW.
N. 45° W., 10° NE	N. 27° E., 12° NW.
N. 45° E., 10° SE	N. 41° W., 13° SW.
Due North, 25° E	N. 30° E., 9° SE.
N. 45° W., 25° NE	N. 85° W., 12° N.
N. 45° E., 25° SE	Due West, 20° S.

The ore body appears to have had a low dip originally; its indicated original strike boxes the compass depending on the initial strike and dip of the Helmet fanglomerate that is assumed. The validity of these restorations and of similar restorations both in and outside the San Xavier thrust plate cannot be appraised until the origin of the rotation of the Helmet fanglomerate is known.

SAN XAVIER THRUST

An undulating low-angle fault, called the San Xavier thrust by Lacy (1959, p. 189), passes beneath the mineralized ground in the northeastern part of the district (pl. 1). The thrust plate includes Precambrian granite, Paleozoic and Cretaceous(?) rocks, intrusive granodiorite and quartz monzonite porphyry, and the Helmet fanglomerate. The overridden rocks are predominantly granite and granodiorite.

SURFACE AND SUBSURFACE EVIDENCE

The San Xavier thrust is exposed at about 10 places between the high hill just northwest of San Xavier and the Ruby Fault near the east side of sec. 22, T. 17 S., R. 12 E. These exposures are characterized by a few inches to a few feet of gouge and intensely sheared or mylonitized rock, generally bordered by hundreds of feet of brecciated, sheared, or shattered rock. One of the best exposures is shown in plate 4.

The observed dips of the fault zone range from 28° to horizontal and are variable in direction. The general dip is to the east from the latitude of San Xavier southward for about 3 miles into the

SW¼SE¼ sec. 21, T. 17 S., R. 12 E. Between this point and the Ruby fault there are north-plunging undulations in the fault zone, resulting in a general northerly dip of the zone. If the interpretation of the geology east of the Ruby fault is correct, the segment of the thrust east of that fault must dip to the northwest. Apparently the thrust plane has the form of a broad trough that plunges to the north-northeast.

Available subsurface information supports the existence of a thrust with the troughlike form inferred above. Ransome (1922, p. 424) reports that the main shaft of the Paymaster mine passed from Cretaceous(?) andesite breccia into rather coarse-grained granite at a depth of 300 feet. Colorado-Utah drill hole No. 1, in the SW¼ sec. 22, T. 17 S., R. 12 E., collared in steeply dipping Helmet fanglomerate, and after passing through a large shear zone, entered sheared and argillized granodiorite at a depth of 201 feet. Drilling near the San Xavier mine has indicated a shear zone which separates Paleozoic and Cretaceous(?) rocks above from granite below and which increases in depth toward the east to a maximum of about 1,200 feet a third of a mile east of the main shaft. Deep exploration northeast of the San Xavier mine, on properties of the Banner Mining Co. and the American Smelting and Refining Co., has also revealed indications of a low-angle fault, called the Basement fault by Richard and Courtright (1959, fig. 43), that increases in depth toward the east and separates ore-bearing rocks above from barren granite below. This fault, here interpreted as the San Xavier thrust, is cut by all drill holes deep enough to reach it. No holes have reached it along the axis of the inferred trough, but a hole on the southeast flank of the trough, in the southern part of sec. 9, T. 17 S., R. 13 E., cut it at a depth of less than 1,000 feet.

TRACE ON THE SURFACE

From the latitude of San Xavier southward as far as the Ruby fault, the course of the San Xavier thrust is revealed by scattered exposures of the thrust zone and by an abrupt change in the character of the topography. The Paleozoic and Cretaceous(?) rocks of the thrust plate are resistant to erosion and form hills, whereas the overridden granite and granodiorite are less resistant and have been eroded to a featureless pediment.

The structure west of Mineral Hill can be interpreted in several ways. The interpretation shown on the geologic map is that the San Xavier thrust passes through the granite west of a group of small fault blocks of mineralized Paleozoic limestone that lie in or on the granite. According to this interpretation, the fault blocks of Paleozoic rock could represent imbricate thrust slices related to the San Xavier

SAN XAVIER THRUST IN NW¼ SEC. 27, T. 17 S., R. 12 E.

thrust, or they could equally well have been emplaced during the earlier, premineralization orogeny. An alternative interpretation, somewhat less likely, is that the San Xavier thrust turns eastward about half a mile northwest of San Xavier and then turns north to pass along the west side of Mineral Hill. According to this interpretation, the small fault blocks of Paleozoic rock could represent klippen of the San Xavier thrust plate.

From the north edge of the map area, the fault trends a little west of south for about 3 miles, and then swings in a sigmoid curve—first to the west, then in turn to the south, east, northeast, and southeast—to the Ruby fault. The curves appear to be due to small changes in strike and dip of the fault zone. The segments that trend east and northeast are sinous because of shallow north-plunging undulations in the zone.

The interpretation that the large east- to northeast-trending fault north of Twin Buttes is an offset segment of the San Xavier thrust (pl. 1) is based on indirect evidence. It is very unlikely that the thrust passes through the Helmet fanglomerate in the eastern part of the area; no break is apparent in the stratigraphic section of this part of the fanglomerate, and the remarkable uniformity of the dip and the strike of the fanglomerate strongly suggest that the parts east and west of the Ruby fault represent a once-continuous block in the thrust plate. The indicated offset of the thrust by the Ruby fault is the smallest offset compatible with the geologic relations. Furthermore, this interpretation provides a reasonable explanation of the very large fault that cuts off the Helmet fanglomerate on the south.

The indicated offset of the thrust could have been accomplished by moderate postthrust movement on the Ruby fault. This fault dips 65° E., and the east side is downthrown. The fanglomerate, which dips southeast, was offset in a left-lateral direction. The thrust, which dips gently to the north, was offset in a right-lateral direction. Planes of reference are too poorly defined to estimate the movement on the Ruby fault, but it could be as little as a few hundred feet.

AGE

If the field evidence has been interpreted correctly and the San Xavier thrust has offset the Helmet fanglomerate, then movement on the thrust must have taken place after ore formation. A postmineralization thrust of this magnitude is so important to the interpretation of the overall structure of the district that the evidence bearing on its age will be reviewed in detail.

The San Xavier thrust unquestionably cuts monolithologic breccias, here somewhat doubtfully assigned to the Helmet fanglomerate (pl. 1); but where the thrust is shown cutting conglomerate beds of the

Helmet, the structural relations are indeterminate because of poor exposures. Obviously no firm conclusion that the thrust is post-Helmet can be drawn from these relations.

The conglomerate units of the Helmet exposed in secs. 15, 21, 22, and 27, T. 17 S., R. 12 E., have the steep southeast dip characteristic of all exposures of the formation. The geologic relations shown on plate 1 suggest that the thrust cuts off the conglomerate on the south and east. Although this part of the thrust is not exposed, the contact between the conglomerate and the granite and granodiorite can be located rather closely and is a sinuous line which connects exposed parts of the thrust and which cuts across the beds of the conglomerate. Data obtained from the Colorado-Utah diamond-drill hole No. 1, which was mentioned previously, support the thrust relation. This hole is vertical and collars high in the red unit of the Helmet fanglomerate in the SW¼ sec. 22. To a depth of 201 feet, the hole cut fanglomerate containing monolithologic breccia lentils or fault slices of arkosic quartzite, granodiorite, andesitic volcanics, and dark porphyry. The core recovery was poor, and the drilling record indicates that very soft zones were found below 150 feet. From 201 feet to the bottom at 284 feet, the hole cut granodiorite. The top 70 feet of the granodiorite is so sheared and argillized that it is almost unrecognizable.

A drill hole in sec. 9, T. 17 S., R. 13 E., further supports a post-Helmet age of the thrust. This hole passed through alluvium into the andesite flow member of the Helmet fanglomerate. It remained in the andesite to a depth of 675 feet and then passed into granite. The contact of the andesite and the granite is clearly a large fault, since it cuts out the red unit of the Helmet and an unknown thickness of pre-Helmet rocks. It is probably a low-dipping fault, for shallower drill holes in the vicinity have cut nothing but alluvium and the Helmet fanglomerate and give no indication that stratigraphic units of the Helmet are offset. Presumably the fault is the San Xavier thrust.

The structural relations of the granodiorite indicate that the San Xavier thrust is younger than the Late Cretaceous–early Tertiary orogeny. Southwest of Twin Buttes, in the vicinity of the Senator Morgan and Contention mines, the granodiorite has intruded large faults and shear zones in the Paleozoic and Cretaceous(?) rocks. The granodiorite is mineralized locally but is not appreciably sheared. Near the Paymaster mine, the San Xavier thrust cuts the granodiorite for several miles, and the granodiorite is much sheared and brecciated (pl. 4). This evidence is incompatible with a Late Cretaceous or early Tertiary origin of the thrust but is compatible with a post-Helmet and postmineralization origin.

If the San Xavier thrust postdates the Helmet fanglomerate, as all the evidence so far presented would indicate, any mineralization products in the thrust zone must either have been dragged into place or have formed in post-Helmet time. I have found no definitive ore-stage minerals in the zone. Traces of supergene chrysocolla and scarce pockets and disseminations of supergene limonite were noted at several places. Feldspathic rocks, such as granite and Cretaceous(?) rhyolite, have been argillized, and some seams and veins of barren quartz have been introduced. The quartz seams are generally associated in space with argillized feldspathic rocks, suggesting that argillization and introduction of quartz are genetically related phenomena. Possibly these phenomena are of supergene origin, for the thrust plate contains sulfide minerals, which, on oxidation, would acidify ground water and make it capable of breaking down silicates into clay, silica, and soluble bases. It is also possible that the argillization and silicification are due to post-Helmet metasomatism. The andesite(?) assigned to the Helmet west of the Ruby fault has been subjected to alkalic metasomatism if my tentative interpretation of the rock is correct (p. 82). This possible late metasomatic episode could have dated from the stage of intrusion of the post-Helmet andesite dikes.

SUGGESTIONS OF DIRECTION OF MOVEMENT

The possible direction of movement along the San Xavier thrust is suggested by three lines of evidence:

1. The Helmet fanglomerate, where exposed, strikes near N. 60° E. and dips about 55° SE. Post-Helmet shortening along N. 30° W.–S. 30° E. lines is indicated. If shortening due to the thrust was in the same direction, one would expect that the thrust plate moved either N. 30° W. or S. 30° E.
2. At the locality shown in plate 4, the San Xavier thrust strikes about N. 36° W. and dips 13° NE. The footwall of the main zone of movement is marked by parallel grooves which trend N. 65° E. These grooves are not slickensides, striae, or mullions, as their cross section is a sharp-angled V, formed at least in part by weathering out of a soft, claylike material. They must be related to the thrust in some way, however; for they occur in sheared granodiorite, an originally homogeneous rock. They may be chatter marks transverse to the direction of movement. If so the indicated direction of movement is N. 25° W. or S. 25° E.
3. Many boulders in the Helmet fanglomerate are broken and offset by tiny faults. At some places the faults extend into the matrix (pl. 3), but generally the faults end at the boulder margin and

seem to express the response of a rigid body to plastic flowage of the enclosing medium. The shear patterns, which must reflect some major deformational event or events in the history of the fanglomerate, have been studied at three localities. (See pl. 5.)

At each locality, the following measurements were made: Strike and dip of every fault with perceptible displacement and direction of displacement of the hanging-wall block of each of these faults. The displacements along the faults measured range from a trace to 0.25 inch. Some measurements of the direction of displacement may be in error by as much as 30°. Fortunately many of the boulders are angular and have exposed sharp edges that reveal the direction of displacement within a few degrees.

Locality A is the outcrop that is partly shown in plate 3 and is 125 feet long. Faults are very abundant and cut matrix as well as boulders. Observations were made at nine equally spaced stations along the outcrop. Twelve faults were measured at one of these stations, and 11 faults were measured at each of the other stations.

Locality B is a large outcrop which has abundant faults, apparently confined to the boulders. Observations were made within an area about 5 by 20 feet in a part of the outcrop selected at random.

Locality C consists of outcrops at two widely spaced places. Faults are very scarce and appear to be confined to the boulders. Observations at each place are scattered over several hundred linear feet of outcrop.

The most striking features brought out by the diagrams (pl. 5) are the low dip of the fault planes and the dominant displacement of the hanging-wall blocks to the northwest. If the faults are related in origin to the San Xavier thrust, the results suggest that the thrust plate may have moved N. 10°–20° W.

HYPOTHESIS REGARDING DISPLACEMENT

The various suggestions of the direction of movement on the San Xavier thrust are compatible with each other and are also compatible with an hypothesis regarding displacement, suggested by certain similarities in the geology of the Mineral Hill–Helmet Peak area and of the area south of Twin Buttes. The hypothesis is that the exposed part of the San Xavier thrust plate originally lay south of Twin Buttes and has been displaced about 6½ miles to the north-northwest in the direction suggested by faulting of boulders in the Helmet fanglomerate.

The hypothesis requires that prethrust rock units and structural features exposed in the Mineral Hill–Helmet Peak area have their roots south of Twin Buttes. To test whether this is probable or possible, one must imagine that the thrust plate is restored to its hypothetical source. If this is done, there is a crude match in the following geologic features:

1. The anticline on Helmet Peak would correspond with the anticline exposed in the isolated outcrop about 1½ miles southeast of Twin Buttes village. Drag folds suggest that the anticline southeast of Twin Buttes plunges about 25° SE. The Helmet Peak anticline plunges about 60° SE. (See table 5.) The Paleozoic rock in the two folds is not greatly metamorphosed and still contains recognizable fossils. The beds exposed in the Helmet Peak anticline (Concha limestone, Scherrer formation, and upper part of Colina limestone) are stratigraphicaly above those exposed in the anticline southeast of Twin Buttes (lower part of Colina limestone and upper part of Earp formation).
2. The Paleozoic rocks forming the hills near San Xavier would correspond with those containing the Senator Morgan and Contention mines. These rocks are much metamorphosed and contain the only significant concentrations of zinc in the district—at the San Xavier and San Xavier Extension mines in the thrust plate and at the Contention mine in the hypothetical footwall block.
3. The Paleozoic limestones of Mineral Hill would correspond with those immediately south of Twin Buttes village. These limestones are much metamorphosed and contain important copper deposits—the Mineral Hill, Daisy, and Pima deposits in the thrust plate and the deposits at the Minnie, King, Queen, and Glance mines in the hypothetical footwall block.
4. The Paleozoic rocks at the Mission deposit (Richard and Courtright, 1959, p. 201) would lie on the projection of the outcrops of Paleozoic rock northeast of Twin Buttes village.
5. The Cretaceous(?) rocks south and southwest of San Xavier would correspond with those south and southwest of the Senator Morgan mine. These rocks include arkose on the northeast and andesite on the southwest, and they contain small vein deposits of silver, lead, and zinc.
6. The Precambrian granite full of included material southwest of Mineral Hill would correspond with that west and southwest of Twin Buttes.

The two outcrop patterns do not match perfectly, nor should they be expected to do so. According to the hypothesis, the bottom of the thrust plate once matched with the footwall block along a shear plane that was an unknown distance above the present surface of the footwall block. To assume that the outcrop patterns should match perfectly is like assuming that the surface geology over a mine should match perfectly with the geology of a very deep level. Furthermore, the thrust plate probably contains unknown imbricate thrusts, tear faults, or other structural complications formed during the thrusting and confined to the thrust plate; such structural features would tend to obscure an original match.

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